# CALIFORNIA INSTITUTE OF TECHNOLOGY

## NORMAN BRIDGE LABORATORY OF PHYSICS

# FINAL REPORT



N6 onr - 244, Task Order IV
(NR 017 - 602)

March 1, 1947 - November 30, 1954



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## Abstract

This final report on Contract N6onr-244, Task Order IV, (NR 017-602), covering the period from its beginning, March 1, 1947, to its termination, November 30, 1954, includes a brief discussion of the entire research carried out under its auspices. References are made to a bibliography which includes all Special Technical Reports and published articles pertaining to accomplishments of this Task.

Work financed by other organizations* is referred to in this report wherever this work has been instrumental in the pursuit of the objectives of the Task.


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* Research Corporation; U.S. Atomic Energy Commission; and Office of Ordnance Research (U.S. Army).

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## I. SUMMARY OF DEVELOPMENT OF 2-METER CURVED CRYSTAL SPECTROMETER (See Fig. 1)

In March 1947, when Contract N6onr-244, Task Order IV came into effect, construction of the 2-meter curved crystal γ-ray spectrometer[1][28] * was well advanced. The idea for this instrument was conceived by the supervisor as early as 1937, and in 1938 construction of the present instrument was started in the shops of this Institute with Physics Department support only. In 1940 the assembly was practically complete (save for the all-important curved crystal, the γ-ray detecting system, and the auxiliary electronic equipment) but at this point progress was interrupted and work on the spectrometer was abandoned for the wartime interval of 1940 to 1946. Thus almost the entire design of this instrument, as well as its mechanical construction were in existence before the subject contract was initiated, although success in its objectives was only achieved after the contract had been in force.

Space limitations allow only the briefest summary of the work done on the curved crystal γ-ray spectrometer. A more complete account is given in Special Technical Reports listed in the attached bibliography and designated by reference numbers. In many cases these Special Technical Reports have also appeared as articles published in scientific journals either before or after their preparation or submission as Special Technical Reports.

The initial work supported by the O.N.R. contract included the development of a multicellular G.M. counter for detection of γ-rays. The unusual requirements imposed on a G.M. counter for this application necessitated a rather long and at many times discouraging period of design development. A successful counter was built[10] and in operation in 1948 but the unpredictable danger of developing unstable operation

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* Throughout this final report, the superscript reference numbers refer to the numbers of Special Technical Reports listed in the bibliography. S.T.R. No. 28 is the most generally comprehensive single source of information on the entire technique of crystal diffraction spectroscopy of short wavelength radiation developed under this contract.

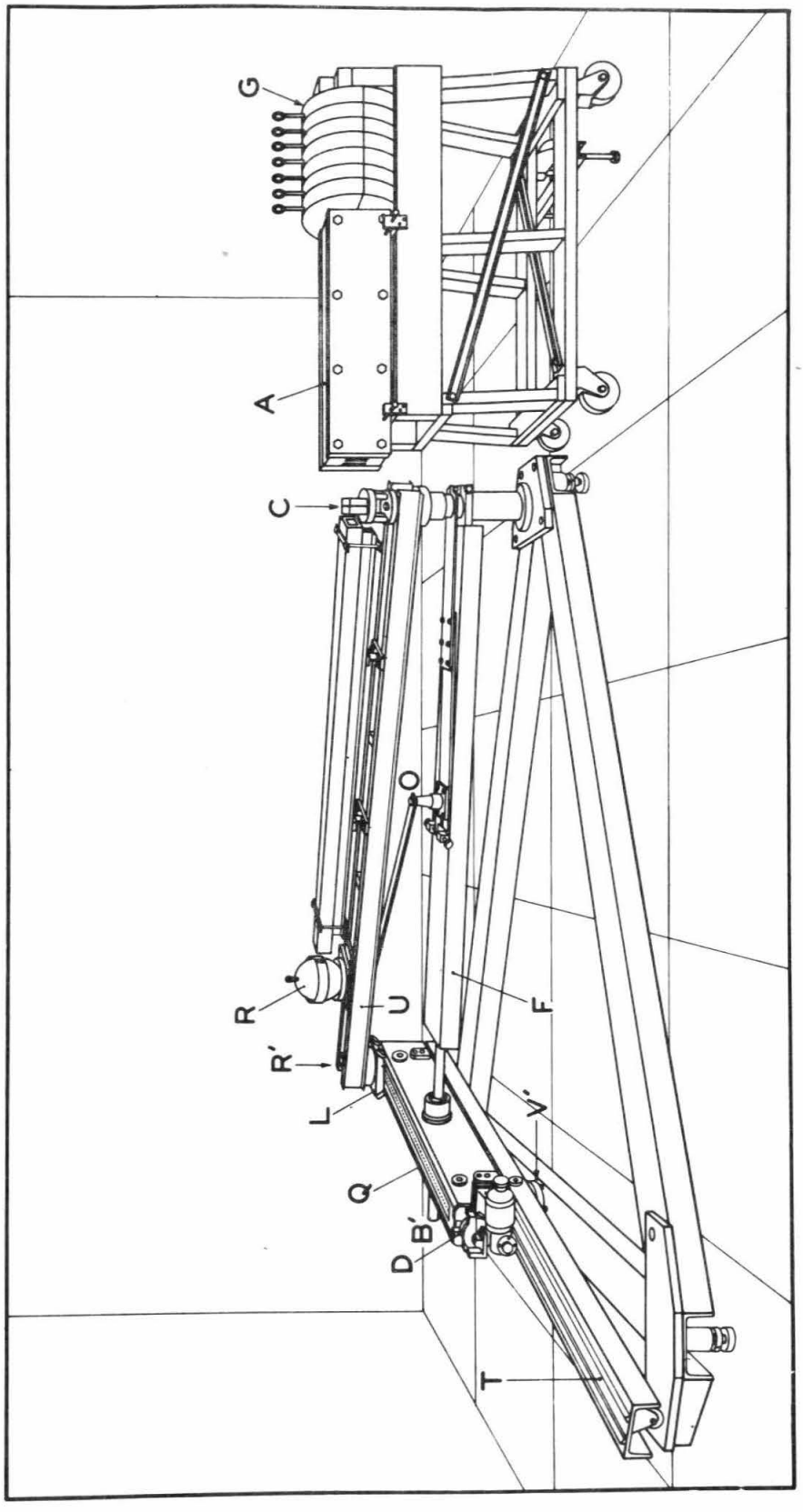


Fig. 1 Perspective line drawing of the gamma-ray spectrometer showing the curved crystal at C and the source in its shielded holder, 2 meters from it, at R.

in this counter without apparent warning or cause and at most annoying times, made its use very trying. Later adoption of an especially designed sodium iodide scintillation crystal[21][28] has solved all these difficulties and has proved both more sensitive and more reliable. This has therefore replaced the earlier G.M. counters completely.

To a large extent the resolution of the spectrometer depends on the quality of the monochromatic beam reflected by the curved quartz crystal. The X-ray and $\gamma$-ray reflection properties of the (310) planes of quartz were investigated over the wavelength domain 500 to 9 x.u. for the transmission case[14]. The plates were inhomogeneously stressed by bending to a circular cylinder of 200 cm. radius. The value of the integrated reflection coefficient was deduced from the luminosity properties of the curved crystal spectrometer for several different wavelengths. The experiment indicated that the integrated reflection coefficient for a bent crystal varies as $\lambda^2$ over the wavelength studied. This behavior is in accord with that of a mosaic crystal. The reflection properties of an unstressed crystal plate cut from the same slab were studied and results indicated that unstressed quartz plates behave more nearly as perfect crystals. To date no completely satisfactory explanation of this mosaic behavior of bent quartz plates has been found. The bending produces no permanent deformation and the plates when released from bending stress return to their original unstressed state and once again behave in that state as "perfect" crystals.

The technique for bending the polished quartz crystal[2][28] and clamping it in a 2-meter radius block has been developed to a high degree of precision. A unique method for profiling the stainless steel clamping blocks to an optically true circular cylinder of large radius was developed that utilizes the machinery available in the average small machine shop. (See Fig. 2)

In the spectrometer the angle of deviation of the monochromatic diffracted beam relative to the heterogeneous incident beam is extremely small. The directly transmitted beam being many orders more intense than the diffracted beam, the former must be prevented from reaching the

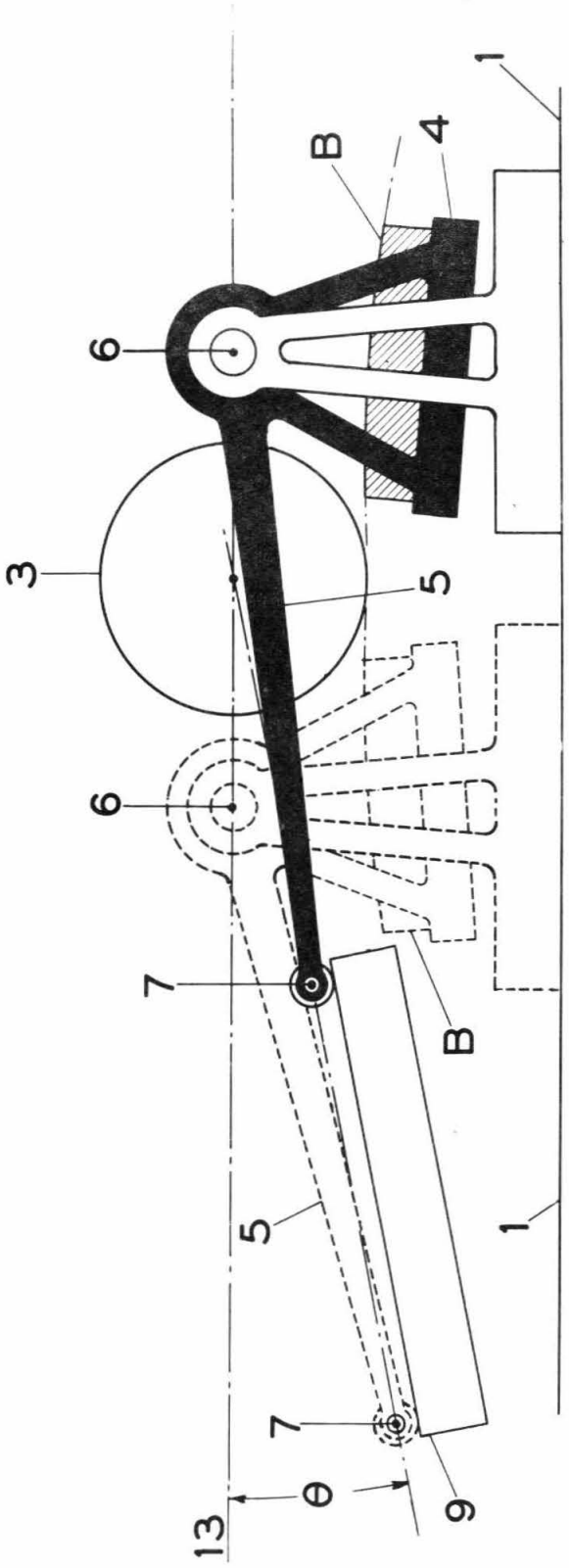


Fig. 2 Schematic view illustrating in principle the method of grinding a convex cylindrical surface of large radius on the surface grinder. This view is not to scale and the curvature of the block is greatly exaggerated for clarity.

counter while impeding the latter from doing so as little as possible. For this purpose a lead-antimony-tin alloy baffle system[28] was constructed with tapered partitions. The geometry of this collimator was worked out carefully, since it sets the lower limit on the minimum wavelength that can be measured. Its geometry plays no part in determining the spectral resolving power of the instrument however.

A good deal of work was done on the determination of the optimum geometry of the radiation source. In many cases the geometry of the source itself plays the role of a spectroscopic slit.[28]

Because of the high resolving power of the instrument an exploratory run on the $\gamma$-ray spectrum of a source not too well known may take as long as 90 hours, if performed in sufficient detail to insure missing none of the lines. Manual operation thus can be so tedious and time consuming that, to facilitate the operation and data recording, an automatic programming robot device[28] has been built along with an electro-mechanical printer. This equipment allows the step-by-step exploration of the spectrum automatically according to a predetermined program without the exposure of personnel to radiation or fatigue.

In 1951 the increased sensitivity gained by the use of the scintillation counter had permitted precision measurements of certain $\gamma$-ray lines with the 2-meter instrument in three different orders of reflection and this work revealed slight discrepancies between the apparent wavelength obtained from the different orders. This raised the suspicion that some unsuspected nonlinearity in the wavelength scale might be present. Since the curved crystal spectrometer was designed primarily to achieve high precision a careful intensive study was therefore made of all possible sources of error[21] in the instrument and an extremely careful recalibration was made as regards the linearity of the wavelength scale. The chief causes of trouble were found to be minute mechanical flexures in some parts of the instrument. Optical means were devised for the detection and measurement of these errors. The resultant calibration curves were used to correct previously published data and these along with the

optical means of detecting and correcting for flexural errors are now used in present experiments.

## II. BRIEF OUTLINE OF SOURCES STUDIED WITH 2-METER CURVED CRYSTAL SPECTROMETER.

In the following section all important studies of artificial and natural radioisotopes made during the life of the contract are briefly mentioned. Space here does not permit the inclusion of a discussion of the techniques and conclusions of each of the experiments. In each case, references are given to the appropriate Special Technical Report.

In early 1948 the curved crystal spectrometer was used to study the 0.41 Mev $\gamma$-ray line from a 1-curie source of $Au^{198}$ (3), of half-life 2.7 days. This measurement marked the first successful operation of the new instrument.

A careful study of the annihilation radiation coming from the recombination of positrons (emitted by $Cu^{64}$) with negative electrons in a solid block of neutron activated copper was made in 1948 and repeated in 1952(21) following the recalibration of the curved crystal spectrometer. The final value obtained for the annihilation radiation ($E_A$ = 510.941 $\pm$ 0.045 kev) is in close agreement with values obtained in the least squares analysis of December 1950(12). The line broadening effect of the thermal velocities of the electron and positron was noted. It was necessary in the precision measurement to determine the amount of distortion contributed by Compton shifted scattering within the $\gamma$-ray source. An analysis(8) proved this effect to be negligible.

By 1949 improvements in the curved crystal spectrometer extended its quantum energy range from 0.5 Mev to well above 1 Mev as well as improving its luminosity and resolving power. This allowed a precision wavelength measurement of the 1.1 and 1.3 Mev line of $Co^{60}$.(13) At that time these lines were the shortest wavelengths ever measured directly (i.e., by crystal diffraction).

The precision inherent in the curved crystal spectrometer made possible an accurate test of the Ritz combination principle as

applied to nuclear γ-rays. In the case of two lines from $I^{131}$, 80 and 284 kev[11], a decay scheme proposed by Metzger and Deutsch was verified to an accuracy of 1 part in 4500 and an alternate proposal invalidated. In the case of $I^{131}$ as in many others, new lines were discovered and the observations of other experimenters have been verified. While primarily designed as a means to measure with high precision particular gamma and X-ray lines, the curved crystal spectrometer has also served as a useful tool to explore in its entirety the γ-spectrum of various isotopes.

A good example of the spectrometer's usefulness as an exploratory device is the case of $Ta^{182}$ [28][21][31] and $Ta^{183}$ [26]. (See Fig. 3) Early in 1950 a series of runs was made on $Ta^{182}$. Subsequent work revealed the presence of then unknown lines of relatively short half-life. These were studied with a stronger source and as promptly as possible after the irradiation of tantalum. Twenty lines were observed and measured with high precision in the range 46 to 355 kev.[26] The presence of the strong $WK\alpha_1$ X-ray line permitted the instrument to be calibrated[30] without the installation on the wavelength carriage of a heavy X-ray tube and its stiff high voltage cables, which was the method used earlier in the study of the W K-spectrum.[5]

Other isotopes which have been studied under the sponsorship of the O.N.R. are Rn, $Ir^{192}$, RaTh, $Cs^{137}$.[21]

Since the 2-meter curved crystal spectrometer gives results directly in X-units to an accuracy of about ± 0.001 x-units, it is essential that the conversion constant λV between X-ray wavelengths and quantum energy in electron volts be established to a high order of precision. To this end an experiment was performed[27] to determine the wavelength in x-units (Siegbahn scale) at the quantum limit of the continuous spectrum from a tungsten target sealed-off X-ray tube operating under an accurately stabilized and measured applied voltage[18] of 24498.7 ± 1.1 absolute volts (3mu). The 2-meter curved crystal spectrometer was used as the monochromator. The value obtained was $\lambda V = 12370.02 \pm 0.63$ emu K x-units. This precision (51 parts per million) warranted the use of this measurement (along with two others made at Johns Hopkins using lower voltages)

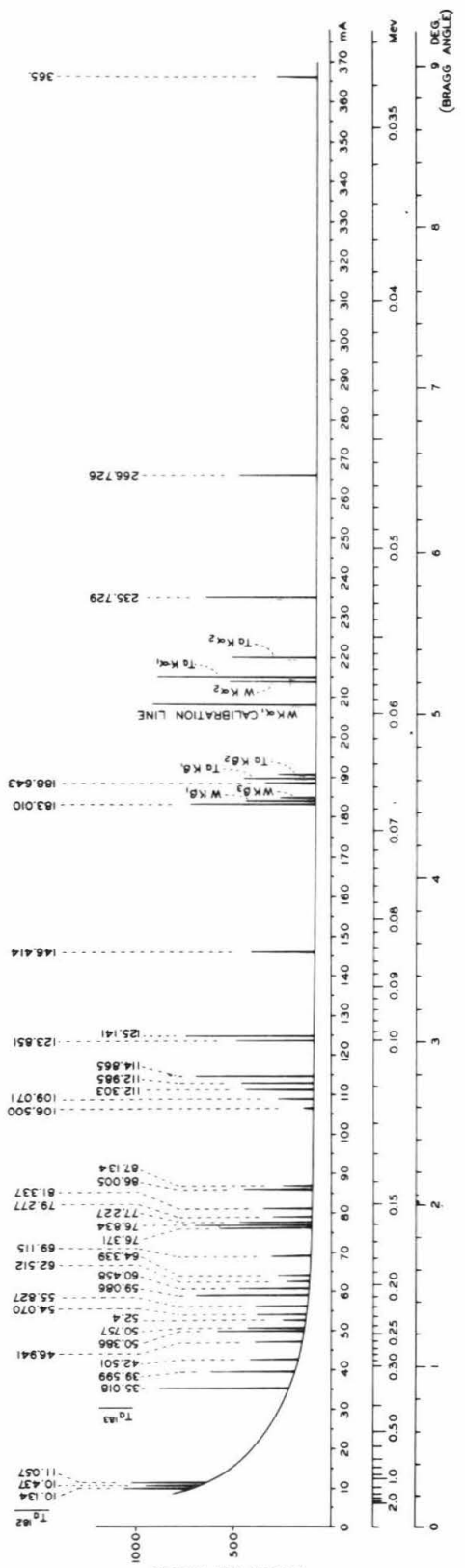


Fig. 3 "Bird's-eye-view" of complete spectrum of gamma-ray and X-ray lines observed with a neutron activated source of $Ta^{182,183}$. The lines appear superimposed on a continuous background of scattering from the walls of the collimaoor, which can be seen to rise rapidly at the smaller angles. Two complete spectra like the one shown here are obtained corresponding to reflection from the two sides of the (310) planes of the quartz crystal and the wavelength of each line is computed by determining thesseparation measured on the wavelength screw between the reflections on either side.

in the least squares adjustment (mentioned later in this report) to determine the "best" values of five fundamental atomic constants. This least-squares adjustment[25] of all available data on the atomic constants, including the above direct determination, has yielded what we consider a still more reliable value of $\lambda V$ since it is representative of all our most recent and reliable sources of information. This is

$$\lambda V = 12372.2 \pm 0.4 \text{ kilovolt x-units}$$

III. AXIAL FOCUSING MAGNETIC β-RAY SPECTROMETER[6][16] COMPANION INSTRUMENT TO THE 2-METER CURVED CRYSTAL SPECTROMETER. (See Figs. 4 and 5)

Though only partially financed by the O.N.R.* the β-ray spectrometer is mentioned because its use is closely linked to the curved crystal spectrometer. Whenever possible a source studied in one instrument is also studied in the other. The same degree of high absolute precision is the aim for both instruments. At present the data obtained from each instrument for the same isotope, are jointly published in a single paper.

On the one hand the quantum energies corresponding to γ-ray wavelengths which have been measured to high absolute precision with the curved crystal spectrometer can be also studied with sources consisting of the same isotopes placed in the β-ray spectrometer. This is done by observing the internal conversion electrons ejected from various atomic levels as a result of transitions between the same nuclear energy levels first referred to, and by this means fiducial points on the energy scale of the β-ray spectrometer in terms of the magnetic field intensities can be accurately established so that the β-ray spectrometer becomes from one point of view an extension of the γ-ray crystal instrument with the advantage of much higher sensitivity to weak sources which would otherwise be inaccessible to the crystal instrument. The β-ray instrument complements the γ-ray

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* Research Corporation; U.S. Atomic Energy Commission; and Office of Ordnance Research (U.S. Army).

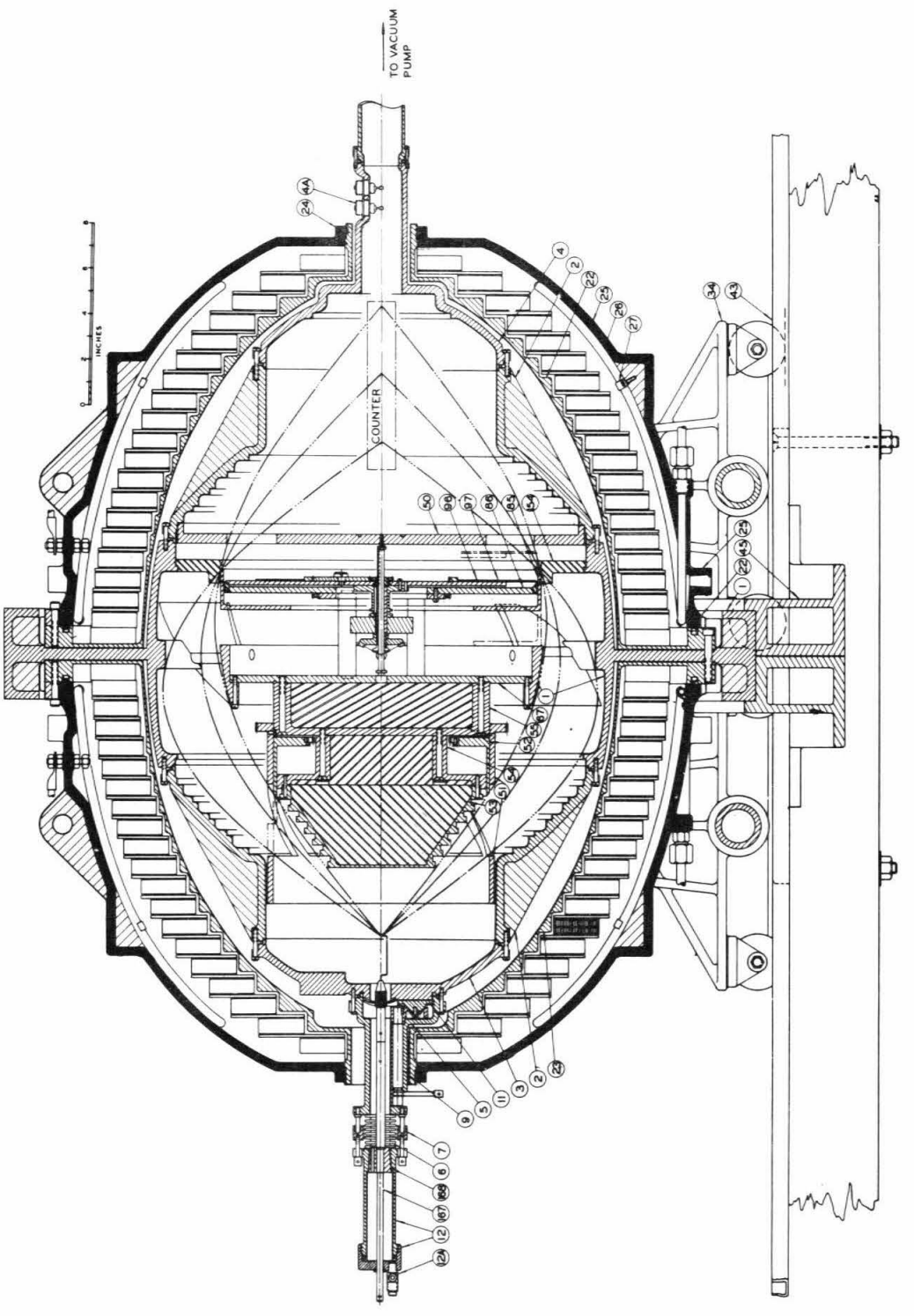


Fig. 4 Complete cross section of homogeneous field magnetic β-ray spectrometer.

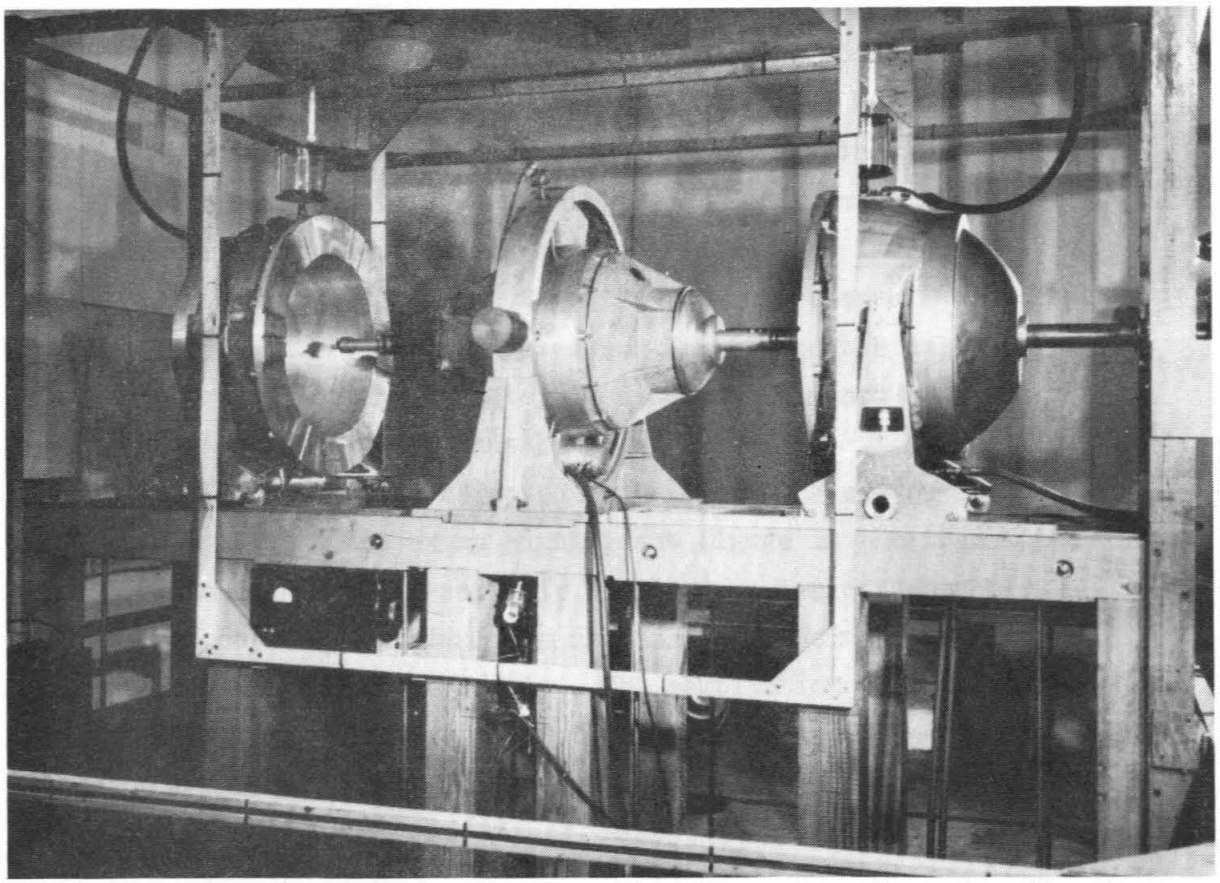

Fig. 5 Side view of the homogeneous field precision β-ray spectrometer with the two halves of the ellipsoidal field coils rolled aside to show the vacuum envelope of the instrument. Portions of the two pairs of Helmholtz coils, which neutralize the transverse components of the earth's magnetic field, are shown. (The component along the axis of the spectrometer does no harm since it is measured, along with the main field, by a proton resonance system.) In this view the source insertion jig has been removed from the source air lock on the left and the microphone connector cable to the pre-amplifier has been removed from its place on the exhaust pipe on the right.

spectrometer in the following ways: (1) its relative energy precision improves with increasing field and energy, while the reverse is true of the crystal instrument. (2) Its resolution remains high while the resolution of the $\gamma$-ray instrument decreases with increasing energies. The cross-over occurs somewhere between 100 and 200 kev.

While both instruments measure energy values, the $\beta$-ray spectrometer supplements the $\gamma$-ray spectrometer in a cardinally important way in that it determines conversion line intensities so that the intensity information from the two instruments leads directly to values for conversion coefficients. From these the multipolarity of each $\gamma$-transition can be determined and assignments of spins and parities of all levels can thus be inferred. (See S.T.R. No. 31).

It should also be noted that in many cases these two instruments provide the extra significant figure in the transition energies that can readily serve to eliminate a large number of tentative decay schemes simply by showing that their transition energies fail to add up correctly. The combination of the two spectrometers has thus been shown to constitute an extremely powerful tool for the establishment of decay schemes even in cases where this decay is extremely complex.

The improvements in the technique of nuclear spectroscopy represented by the two companion instruments developed under this contract are, at the date of writing this final report, beginning to bear fruit. It has been the supervisor's conviction since long before the beginning of the contract that the problem of systematizing and explaining nuclear energy levels could best be solved in its experimental aspects by devising means of getting more accurate, more reliable, and more complete information about level schemes. Many physicists have felt that the inner mechanism of nuclei especially those of higher mass numbers, was too complex to admit of systematic interpretation but now it appears that it is precisely in the field of the heavier nuclei that the first successful efforts in this direction are being made by A. Bohr and B.R. Mottelson with their theory of collective nuclear rotational and vibrational states. It is a source

of considerable satisfaction therefore to be able to report that Prof. A. Bohr and his group have found the results obtained on the energy level schemes of $W^{182}$ and $W^{183}$ by Drs. P. Marmier, F. Boehm, and J. Murray of considerable significance as examples corroborative of their theory. The possibility of obtaining complete information, not only regarding the accurate energy values of the transitions but also the intensities of the gamma and internally converted beta rays, the conversion coefficients and from these the multipolarities of the transitions and the spins and parities of the levels has given Prof. Bohr and his group the opportunity to draw important conclusions regarding the selection rules which govern transitions between the various nuclear states. In the case of the even-even nucleus $W^{182}$, Prof. Bohr and his group have succeeded in classifying the level scheme worked out by Marmier, Boehm, and Murray into as many as three distinct series of rotational states in each of which three or more levels are populated and for which the energy values stand in ratios which agree with their theory to 0.1 percent. (A fourth rotational series is also inferred but since only one of its levels is populated, no quantitative check can be made regarding energy ratios.) These matters are discussed in a paper, "Intensity Rules for Nuclear Data and Gamma Transitions to Rotational States," by G. Alaga, K. Alder, A. Bohr and B.R. Mottelson now in press and to appear in the Dan. Met. Fys. Medd. in the next few months.

## IV. ADVANCES IN OUR KNOWLEDGE OF THE ATOMIC CONSTANTS.

Improved experimental methods of measurement, derived largely from the recent great development of microwave and atomic beam techniques have introduced so much more precision into our general knowledge of the atomic constants that earlier least-squares adjustments of the fundamental atomic constants are obsolete.

Space does not permit a discussion in this final report of the background of the problem raised by the recent advances in our knowledge of the numerical values of atomic constants. Complete descriptions of the input data and techniques used in the least-squares

adjustment of these values along with the resultant data are given elsewhere[9][12][17][25][29]. Reference (25) gives the latest and most up-to-date general account of this work.

A portion of the work published in the Special Technical Reports cited above was jointly financed by the O.N.R. and the A.E.C. A very active world-wide demand for these reports (and reprints of articles based on them) has developed.

## V. DEVELOPMENT OF NEW TECHNIQUES FOR LOW ANGLE X-RAY DIFFRACTION.

### 1. A Point-Focusing X-Ray Monochromator using Two Curved Crystals (In Tandem) for the Study of Low Angle Diffraction. (See Figs. 6 and 7)

Up until recently, most low angle X-ray scattering work has been done with X-ray beams monochromatized, if at all, only by means of filters and collimated by means of pinholes or slit systems. In 1951 a point-focusing X-ray monochromator was designed and constructed for low angle studies[15][19]. The anastigmatic point focus is achieved by means of two cylindrically bent quartz crystals whose focal circles are mutually perpendicular. The beam, emanating from the copper target of an X-ray tube, is reflected in succession, first from the crystal defining the horizontal focal circle which focuses the beam to a line, and second from the crystal defining the vertical focal circle following which it comes to a monochromatic point focus of wavelength 1.537 A ($CuK\alpha_1$). The sample to be studied is placed between the second crystal and the point focus, and the scattered beam is detected by means of a photographic film placed at the point focus. The special geometry requisite to make this focusing anastigmatic has been described in our reports.

This technique obviates the obstacle encountered in the study of wet samples in the electron microscope, where a good vacuum must be maintained, since the sample in the point-focusing monochromator is surrounded by an atmosphere of helium. In many cases, the nature

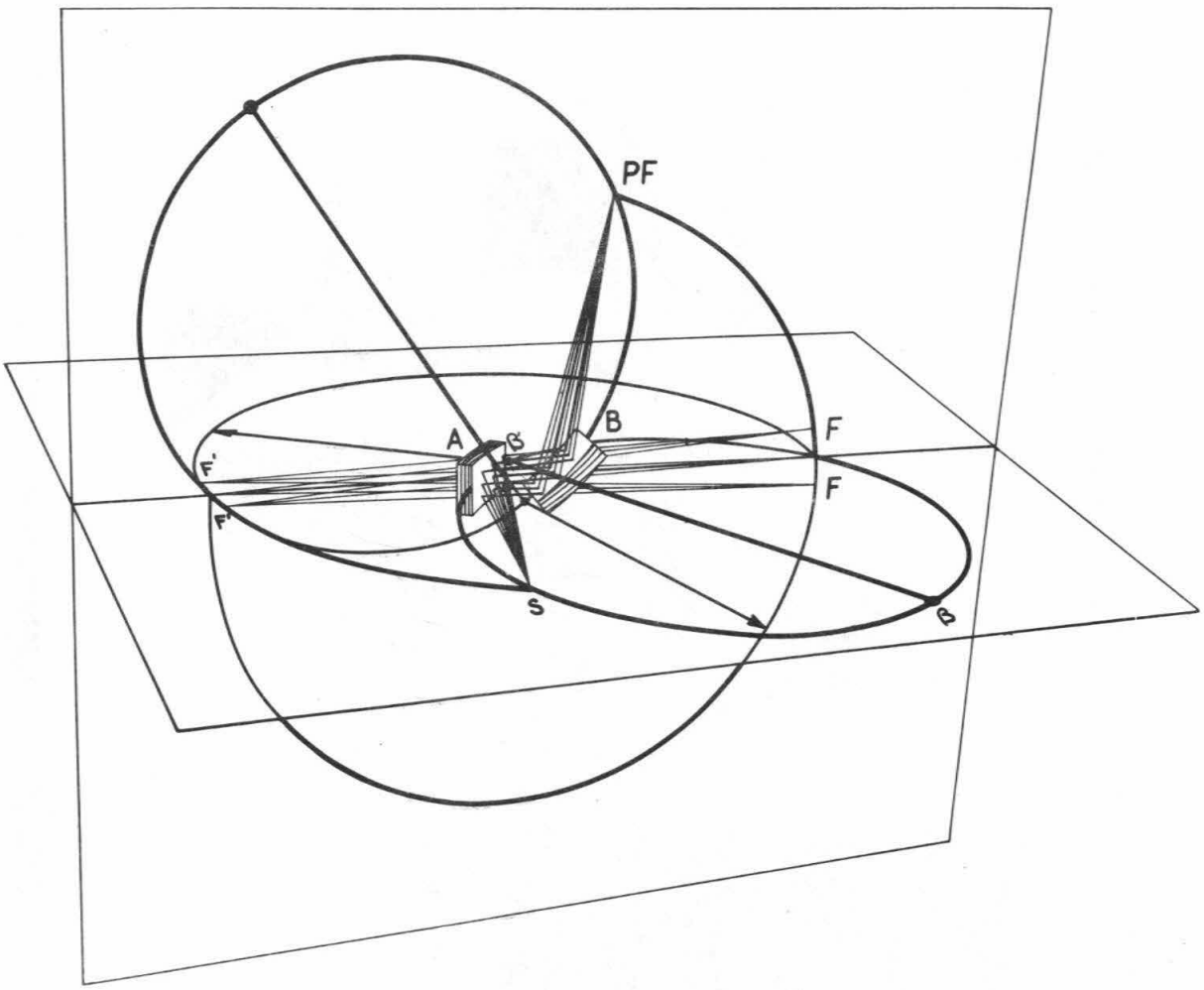


Fig. 6 Perspective line drawing of the 2-crystal point-focusing X-ray monochromator. The X-ray beam emanating from S is successively reflected by crystals A and B and thus brought to a point focus at PF.

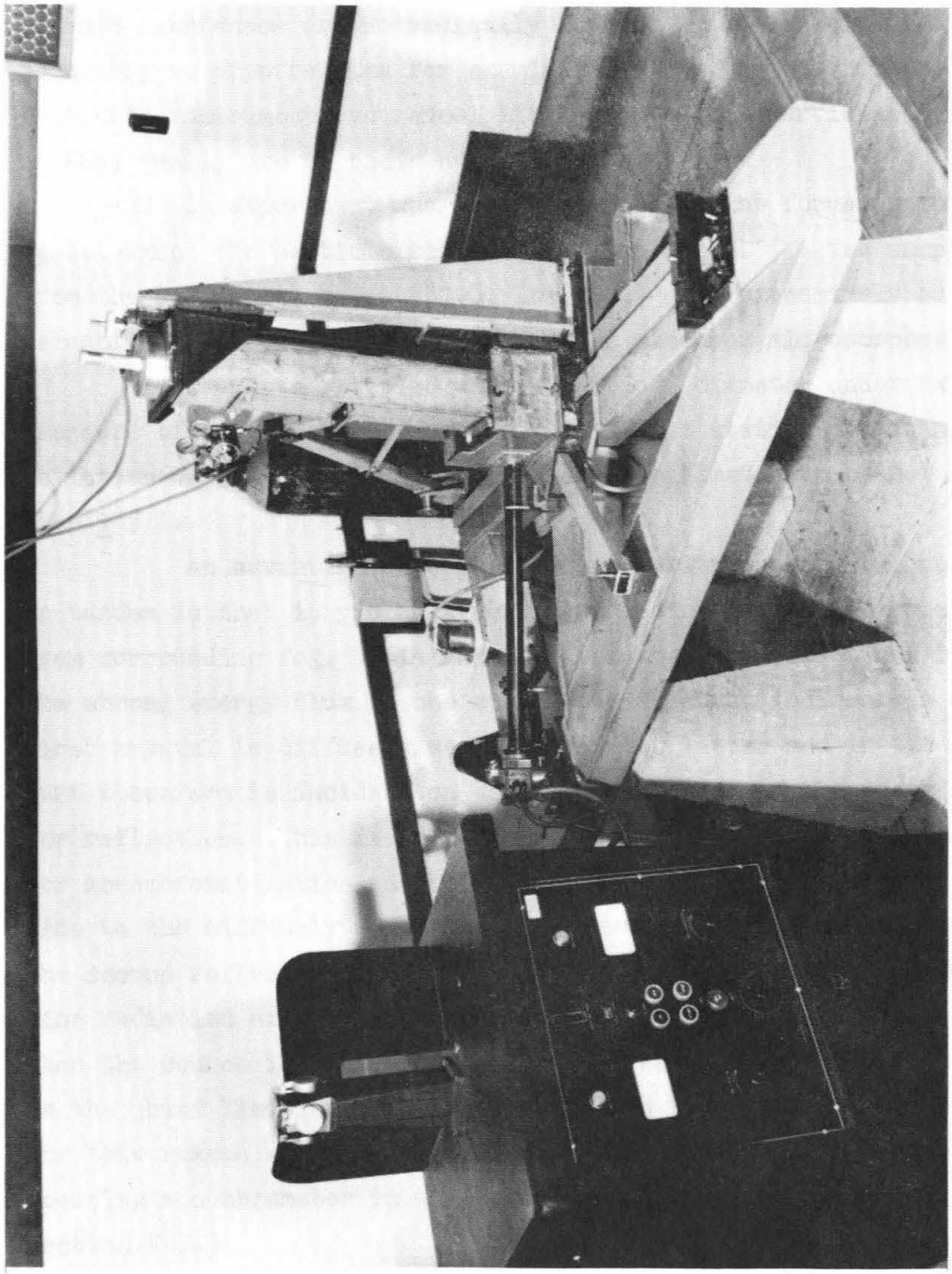

Fig. 7 The complete 2-crystal point focusing monochromator as used in low-angle diffraction studies.

and geometry of the particles or molecules of interesting organic substances are so radically changed by the dessication process necessary to prepare them for examination with the electron microscope that this instrument can reveal little about such particles or molecules as they really are in their natural state.

An experiment was made, using the point focusing monochromator, to determine the particle size of latex spheres.[20] The sample was from the Dow latex, batch 580-G, lot 3584, used extensively as a valuable comparison standard of size for electron microscopes.

The data revealed a mean particle diameter under external pressure of one atmosphere of 2687.5 A with a statistical standard deviation of 1.2 A and a systematic error estimated to be not more than $\pm$ 7 A.

An advantage of this instrument with two crystal reflections in tandem is that it yields a very clean point focus with great freedom from surrounding fog. This results from the two-reflections in tandem. The strong energy flux of the continuous spectrum incident on the first crystal is diffusely scattered by the latter and in the most part therefore is incident on the second crystal at the wrong angle for reflection. This is not true however of the spectral line selected for monochromatization and hence the ratio of the intensity of this line to the diffusely scattered background is very much enhanced after the second reflection. The absolute intensity of the monochromatic line radiation after the two reflections is unfortunately rather low, when the source is an ordinary X-ray diffraction type tube, and this is the chief limiting disadvantage of this two-crystal arrangement. For this reason work has continued in an effort to obtain a point-focusing monochromator in which less intensity is sacrificed. (See Section V-3.)

2. Low Angle X-Ray Diffraction with Long Wavelengths. (See Fig. 8)

The use of long wavelengths, i.e., 13.3 A in the investigation of submicroscopic structures is of considerable interest for the

PHOTO-TUBE AND FILM

SAMPLE HOLDER AND ELLIPSOIDAL MIRROR

POINT SOURCE GAS X-RAY TUBE

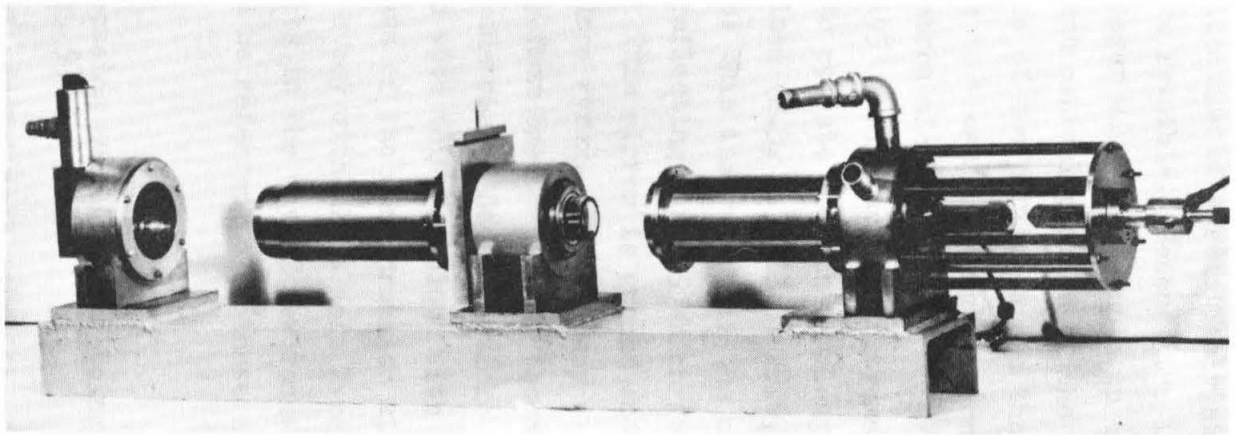

Fig. 8 FOCUSING, LONG WAVE LENGTH, LOW-ANGLE DIFFRACTION CAMERA

following reasons. First, the effects of multiple scattering, multiple refractions, and of electron density fluctuations within the particles can be made vanishingly small for these wavelengths. This makes the direct application of a relatively simple theory of low angle diffraction more feasible. Second, the larger angles of scattering for the longer wavelengths open up to experimental observation the very important central portion of the diffraction pattern. And finally, the sizes of the particles and the thinness of the sample mountings appropriate to these wavelengths permit direct comparison studies with the electron microscope.

Early in 1953 a diffraction instrument was designed and constructed[23][24] to operate at such wavelengths as Cr-K, Al-K, Cu-L, O-K, and C-K lines (2.3, 8.3, 13.3, 23.6, and 44.5 A respectively). The central feature of this instrument is the use of a nearly cylindrical totally reflecting mirror, which forms a point-focused image of the source. This mirror is ground and polished into an ellipsoidal section from Pyrex. In this way a solid angle of radiation is used which is from one to several thousand times that of comparable pinhole geometries. Latex particle sizes have also been accurately determined with this technique with results in accord with those obtained by means of the monochromator with two crystals in tandem. This unique study with ultra soft X-rays has yielded numerous interesting by-products in the way of new research possibilities. The report[24] should be referred to as these are too numerous for recital here.

3. Point-Focusing Monochromator Using a Single Crystal. (See Fig. 9)

A number of crystal type point-focusing X-ray monochromators have been designed, using either two cylindrically bent crystals[19] or one crystal deformed into a non-developable surface.* The first type produces a point focus of very low intensity because it requires

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* See, for example, J. Despujols, Compt. rend. 235, 716 (1952) or Hagg and Karlsson, Acta Cryst. 6, 728 (1952)

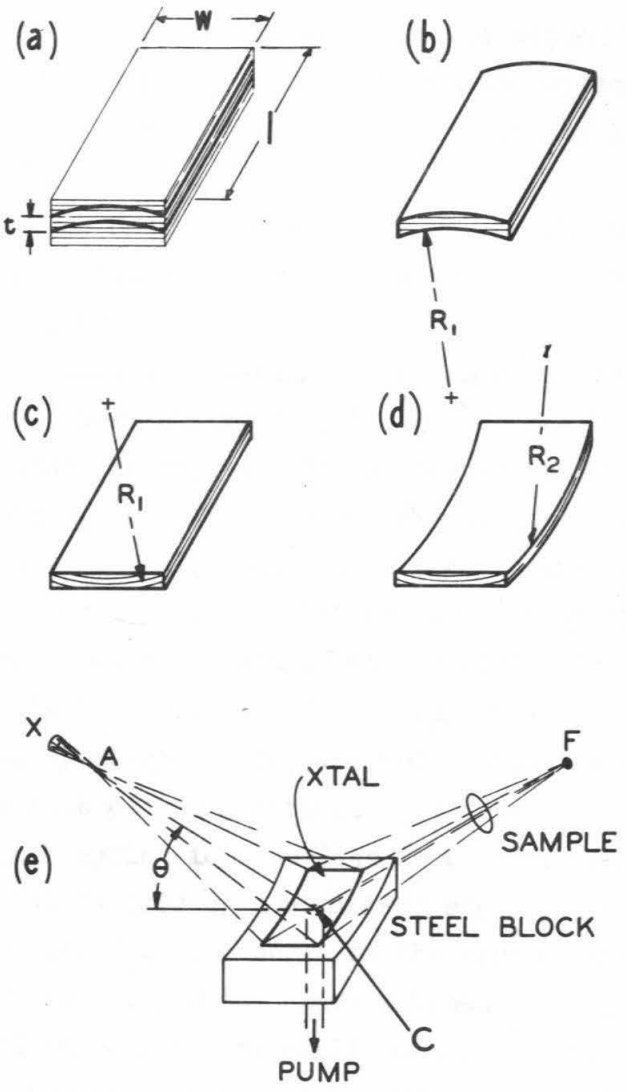


Fig. 9 Process of making single crystal monochromator.

(a) Original block of quartz: w = 3.8 cm, l = 7.6 cm, t = 0.025 cm.

(b) Finished lamina: $R_1$ = 105 cm.

(c) Flattened lamina.

(d) Final shape: $R_2 = R_1 \sin^2\theta$ = 95 cm.

(e) Mounting and X-ray beam: $\overline{AC} = \overline{CF} = R_1 \sin\theta$, $\theta = 71^\circ 42'$.

two successive reflections of the beam. In the second type, the strains produced by bending to a non-developable surface often introduce deformations in the crystal structure which seriously limit the sharpness of the focus.

A method is described here for cutting and bending a single crystal for a point focusing monochromator which does not produce a non-developable surface.

A thin cylindrical lamina of radius $R_1$ is cut from a piece of flawless quartz ( see (a) and (b), Fig.9 ). The lamina is then pressed flat, so that the crystal planes themselves are bent to a radius of curvature $R_1$ ( (c), Fig. 9 ). Finally the flattened lamina is bent to conform to a cylindrical surface of radius $R_2$, the axis of which is perpendicular to the axis of the first cylinder ( (d), Fig.9 ).

The X-ray source is placed at X behind a small aperture A, and a point focus is produced at F ( (e), Fig. 9). The point focus is an image of the aperture so that the beam intensity is essentially determined by the size of the aperture.

The final cylindrical surface is obtained in the following manner: The crystal is laid on a stainless steel block which is ground and lapped to a radius $R_2$. The edges of the crystal are sealed to the steel block with beeswax, and the space between the crystal and the block is evacuated through a very small hole in the block ( (e), Fig. 9 ). The atmospheric pressure is then sufficient to hold the crystal in contact with the block. This method of mounting the crystal proved to be far superior to clamping it between two frames.

Thus far the smallest diameter obtained for the point focus is a few tenths of a millimeter, so that an aperture of about 0.25 mm diameter gives almost maximum resolution. Using this aperture, diffraction patterns of oriented collagen chains were visible out to the fourth order in exposures of less than two hours, or about one fiftieth the time required for a comparable exposure using the same sample and X-ray source with a two-crystal monochromator.[19] The size of the focal spot is about twice that of the two-crystal monochromator, but it is several times as large as can be accounted for by

geometrical aberrations. Hence one should be able to improve the resolution by using more accurate cylinders.

## VI. THE SINE MEASURING INTERFEROMETER FOR THE PROPOSED NEW CURVED CRYSTAL GAMMA-RAY SPECTROMETER (28)

Early in 1952, work was started on a new curved crystal γ-ray spectrometer. The plan was to measure with high precision the sine of the angle of rotation of the curved crystal relative to a fixed γ-ray source. To this end a unique interferometer was designed which when completed would allow the measurement of the change in γ-ray wavelength to a microangstrom.

Progress on this new venture has been halted for the present due to a number of reasons. The great improvement in precision of measuring the Bragg angle of reflection would be wasted unless other aspects of the instrument were refined to comparable order. This has presented many vexing problems. The lack of assurance of adequate funds for so ambitious a project is perhaps the main stumbling block at the present time.

## VII. IN CLOSING.

Contract N6onr-244, Task Order IV (NR 017-602) between the U.S. Office of Naval Research and the California Institute of Technology has been in force for seven and one-half years. As the development of the techniques with which it was concerned progressed, the activities of the contract expanded and in its later stages valuable financial assistance from the Atomic Energy Commission contributed also to its support. The construction of the homogeneous field β-spectrometer was financed by three generous grants from the Research Corporation and, after this instrument was placed in operation, additional funds for its support were made available by a contract with the Office of Ordnance Research (U.S. Army). Although this final report marks the termination of the original research contract with the Office of Naval Research, the general program of work will not ...

be interrupted but will continue under a new contract with the Atomic Energy Commission under which the entire activity will be consolidated in one contractual arrangement.

The products of the seven and one-half year period of support of this research may be briefly summarized as represented in 29 published papers, 31 Special Technical Reports, 2 of which have not been published as papers, and 30 Quarterly Interim Reports. 12 graduate students of this Institute have prepared theses for their Ph.D. degrees in physics through the support given by the sponsors during the seven and one-half year period. 16 graduate students and 11 undergraduate students have been gainfully employed in the research activities of the contract and have thus been facilitated financially toward their education while obtaining experience in research in physics.

In the opinion of the supervisor, the most significant research accomplishment during the period of this contract has been the development of the techniques of precision spectroscopy of nuclear energy levels by the combined use of the two unique instruments developed under this contract, the precision crystal diffraction $\gamma$-ray instrument with the precision $\beta$-ray instrument. The power of this combination is exemplified by the recent resolution of the complete decay scheme in such complicated cases as $W^{182}$ and $W^{183}$, permitting complete specification of level energies, level arrangement, conversion coefficients, multipolarities of transitions and spins and parities of all levels. The case of $W^{182}$ in particular has proven to be of great interest for the new Bohr-Mottelson theory of collective nuclear motion wherein a beginning is being made toward an understanding and a systematics of nuclear spectra. (See Sections I, II, and III of this final report.) Measurements of $\gamma$-ray energies made with the 2-meter $\gamma$-ray spectrometer of this project have come to be widely accepted and quoted as standards for $\beta$-ray and scintillation crystal spectroscopy.

The closing of the seven and one-half years of active and pleasant relationship with O.N.R. personnel both in the local office in Pasadena and the home office in Washington, D.C. brings with it a distinct feeling of regret but also of deep appreciation and gratitude for the intelligent and understanding manner in which the sponsorship has been conducted.

# Bibliography

## SPECIAL TECHNICAL REPORTS

Contract No. N6onr-244, Task Order IV
(NR 017-602)

(1) A High Resolving Power, Curved Crystal Focusing Spectrometer for Short Wavelength X-Rays and Gamma-Rays.

J.W.M. DuMond, Rev. Sci. Instr. 18, 626-638 (1947)

Description is given of the 2-meter curved crystal spectrometer including its theory and geometry, with detailed discussion of the multicellular G.M. counting tube, collimator, crystal and its clamping blocks.

(2) A Precision Method of Generating Circular Cylindrical Surfaces of Large Radius of Curvature for Use in the Curved Crystal Spectrometer.

J.W.M. DuMond, D.A. Lind, and E.R. Cohen, Rev. Sci. Instr. 18, 617-626 (1947)

A method is described for generating circular cylindrical surfaces of large radius of curvature on blocks of steel or other material with a close approach to optical precision utilizing an ordinary machine shop surface grinder.

(3) Precision Wavelength and Energy Measurement of Gamma Rays from $Au^{198}$ with a Focusing Quartz Crystal Spectrometer.

J.W.M. DuMond, D.A. Lind, and B.B. Watson, Phys. Rev. 73, 73, 1392-1394 (1948)

A description is given of the technique used and values obtained for the 0.41 Mev line of $Au^{198}$. (With improvements in the $\gamma$-ray spectrometer as regards absolute accuracy, these results have been revised, See S.T.R. No. 21)

(4) Presence of 0.208 Mev and 0.157 Mev Gamma-Ray Lines in a Sample of the Radioisotope $Au^{198}$.

(Not published elsewhere.)

A short discussion of further early experiments with $Au^{198}$.

(5) A Precision Study of the Tungsten K-Spectrum Using the 2-Meter Focusing Curved Crystal Spectrometer.

B.B. Watson, W.J. West, D.A. Lind, and J.W.M. DuMond, Phys. Rev. 75, 505-512 (1949)

The curved crystal spectrometer was used to measure the wavelengths of the K-series lines and K-absorption edge of tungsten, establishing a precision linkage between wavelength measurements in the $\gamma$-ray and X-ray regions.* Discussion is given of the complete resolution of the $\beta$-doublet, the partial resolution of the $\gamma$-doublet and the detection and measurement of the $\delta$-line close to the absorption edge. Absolute determinations of the Bragg angles for Mo K $\alpha_1$ and WK $\alpha_1$ reflected from the (310) planes of quartz in the two crystal spectrometer are described.

* (With improvements in the $\gamma$-ray spectrometer as regards absolute accuracy these results have been revised, see S.T.R. No. 30.)

(6) Conditions for Optimum Luminosity and Energy Resolution in an Axial $\beta$-ray Spectrometer with Homogeneous Magnetic Field.

J.W.M. DuMond, Rev. Sci. Instr. 20, 160-169 (1949)

Formulas are given for the optimum geometry and dimensions, the energy, resolution and the luminosity of a $\beta$-ray spectrometer with axial homogeneous field. The combined effect of three independent sources of instrumental energy line width is analyzed for the optimum condition. (This theory is the one followed in the $\beta$-ray spectrometer constructed for use by the group working with this contract.)

(7) Precision Measurement of the Wavelength and Spectral Profile of the Annihilation Radiation from $Cu^{64}$ with the Two-Meter Curved Crystal Spectrometer.

J.W.M. DuMond, D.A. Lind, and B.B. Watson, Phys. Rev. 75, 1226-1239 (1949)

Using a source of 2.5 curies of $Cu^{64}$, a sharp annihilation radiation line substantially symmetrical to within the precision of our observations was obtained. The measured wavelength at the peak of this line after conversion from Siegbahn scale of x-units to Angstroms was 0.024271 $\pm$ 0.000010 Å. The broadening of the profile of the observed annihilation line is discussed. (With improvements in the $\gamma$-ray spectrometer as regards absolute accuracy, these results have been revised. See S.T.R. No. 21).

(8) Inappreciable Effect of Compton Shifted Scattering, within a Gamma-Ray Source, on Precision Wavelength Determinations With the Focusing Crystal Spectrometer.

J.W.M. DuMond, Phys. Rev. 75, 1266 (1949)

A short discussion is given of an analysis of the effect of Compton shifted scattering as it pertains to the profile of the $Cu^{64}$ annihilation line.

(9) Recent Changes and Additions in the Consistency Diagram of the Natural Atomic Constants.

J.W.M. DuMond, Phys. Rev. 75, 1267 (1949)

A short discussion of the effect of three new precision measurements on the values of the atomic constants is given. An isometric consistency chart is shown with the three new values shown.

(10) Design and Performance of a Multicellular Geiger Counter for Gamma-Radiation.

D.A. Lind, Rev. Sci. Instr. 20, 233-235 (1949)

The design problems for Geiger counters which have a high $\gamma$-radiation sensitivity are discussed. A description of a Geiger counter consisting of nine individual counters in the shape of thin walled pill boxes mounted inside a single envelope is given.

(11) Precision Measurements of Gamma-Rays from $I^{131}$ with the 2-meter Focusing Curved Crystal Spectrometer.

D.A. Lind, J. Brown, D. Klein, D.Muller, and J.W.M. DuMond, Phys. Rev. 75, 1544-1545 (1949)

The precision measurement of three lines of $I^{131}$ (364.18 $\pm$ 0.1, 80.133 $\pm$ 0.005, 284.13 $\pm$ 0.1 kev) is described. These values are shown to verify one proposed decay scheme and invalidate another.

(12) The "1947 Values" of the Atomic Constants and the Revision of the Faraday Constant.

J.W.M. DuMond and E.R. Cohen, Rev. Mod. Phys. 20, 82 (1948)

The purpose of this short report is to point out that new experimental determinations of the Faraday corroborate the revised value shown in the 1948 least-squares analysis of the atomic constants.

(13) Precision Wavelength Measurement of the 1.1 and 1.3 Mev Lines of $Co^{60}$ with the Two-Meter Focusing Curved Crystal Spectrometer.

D.A. Lind, J.R. Brown, and J.W.M. DuMond, Phys. Rev. 76, 1838-1843 (1949)

Recent improvements in the 2-meter spectrometer are described which have extended its quantum energy range well above 1 Mev and have yielded much better luminosity

and resolving power. The improved components are the curved crystal and collimator. Wavelengths of two $\gamma$-rays emitted following $\beta$-decay of $Co^{60}$ were measured having the value $(9.308 \pm 0.005) \times 10^{-11}$ cm and $(10.580 \pm 0.005) \times 10^{-11}$ cm.

(14) X-Ray and Gamma-Ray Reflection Properties from 500 X-Units to Nine X-Units of Unstressed and of Bent Quartz Plates for Use in the Two-Meter Curved Crystal Focusing Gamma-Ray Spectrometer.

D.A. Lind, W.J. West, and J.W.M. DuMond, Phys. Rev. 77, 475-490 (1950)

The value of the integrated reflection coefficient was deduced from the luminosity properties of a bent crystal in the curved crystal spectrometer, and for unstressed flat crystals in the two crystal spectrometer. Included is a discussion of the fact that stressed plates behave as a mosaic crystal with the reflection coefficient proportional to $\lambda^2$ while in a flat crystal the coefficient is proportional to $\lambda^{3/2}$ [3], or thereabouts.

(15) A Point Focusing Monochromator for the Study of Low Angle X-Ray Diffraction.

L. Shenfil, W.E. Danielson, and J.W.M. DuMond (October 1951) (Not published elsewhere in this extended version. See however S.T.R.'s 19 and 20)

This 91 page report is a rather complete discussion of the work done under O.N.R. contract on the two-crystal point focusing X-ray monochromator. The theory and construction of the instrument including the history of instruments for the study of low angle X-ray scattering is presented. Experiments are described dealing with a precision determination of the size of Dow Latex spheres.

(16) An Axial Focusing Magnetic β-Ray Spectrometer of High Luminosity, Resolving Power and Precision with Proton-Resonance-Stabilized Homogeneous Field - Without Iron.

J.W.M. DuMond, L. Bogart, J. Kohl, D.E. Muller, and J.R. Wilts. (Not published elsewhere in this extended form.)

This is an extensive report (51 pages) comprising the theory, design, construction and tests of the new β-ray spectrometer. It reviews much of the work referred to in previous reports and publications. Some of the conclusions of the report have had to be revised in the light of later findings and these changes of view are given in two sets of extra mimeographed sheets which should accompany each copy of the report (not bound therewith).

(17) Recent Advances in Our Knowledge of the Numerical Values of the Fundamental Atomic Constants.

J.W.M. DuMond and E.R. Cohen, Am. Sci. 40, 447-467 (1952)

A discussion is given of the need for a comprehensive readjustment in the values of the atomic constants. Input data are tabulated and a table of output values is shown. The methods used in the readjustments are described. This paper is now superseded with values based on later and still more accurate data.

(18) A Precision Megohm Ratio Unit for High Voltage Measurements.

J.N. Harris, Rev. Sci. Instr. 23, 409-413 (1952)

A precision megohm ratio unit of 100 resistance units wound of manganin wire is described. Stability is of the order of a few parts per million and variations due to temperature changes are essentially eliminated. A general method is described for setting up accurate resistance ratios by comparing two groups of resistors in appropriate series and parallel arrangements. This equipment was developed for use in the work described under reference (27).

It is now also serving for precision measurements of e/m under way at this Institute under the direction of Professor W.R. Smythe.

(19) A Point Focusing X-Ray Monochromator for the Study of Low Angle Diffraction.

L. Shenfil, W. Danielson, and J.W.M. DuMond, J. Appl. Phys. 23, 854-859 (1952)

A description is given of the point focusing, two crystal monochromator. This published paper is a condensed version of certain material covered more fully in S.T.R. No. 15.

(20) Latex Particle Size Determination Using Diffraction Peaks Obtained with the Point Focusing X-Ray Monochromator.

W.E. Danielson, L. Shenfil, and J.W.M. DuMond, J. Appl. Phys. 23, 860-865 (1952)

A description is given of the results of experiments made using the point focusing two-crystal monochromator as the primary tool to determine the size of latex spheres. The suitability of the instrument for this particular study is described and the experimental data obtained are tabulated. This published paper is a condensed version of certain material covered more fully in S.T.R. No. 15.

(21) Precision Measurements of Nuclear $\gamma$-Ray Wavelengths of $Ir^{192}$, $Ta^{182}$, RaTh, Rn, $W^{187}$, $Cs^{137}$, $Au^{198}$, and Annihilation Radiation.

D.E. Muller, H.C. Hoyt, D.J. Klein, and J.W.M. DuMond, Phys. Rev. 88, 775-793 (1952)

The new calibration experiments of the 2-meter curved crystal spectrometer are described and correction curves are shown. The new sodium iodide counter is described. Precision measurements of the wavelengths and energies of nuclear $\gamma$-rays and X-rays which follow the

decay of $Ir^{192}$, $Ta^{182}$, RaTh, Rn, $W^{187}$, $Cs^{137}$ and $Au^{198}$ as well as the annihilation radiation from $Cu^{64}$ are tabulated. Description is given of how certain small systematic errors (departures from linearity of the wavelength scale) were detected as a result of comparing the same wavelength reflected in different order. The explanation of these errors in terms of imperfect rigidity of certain parts of the instrument is given and the optical means of determining a correction for these errors is described.

(22) Higher Precision in Nuclear Spectroscopy.
J.W.M. DuMond, Physics Today 5, 13-20 (November 1952)

The desirability of higher precision in nuclear spectroscopy is discussed. The two-meter curved crystal spectrometer is described. The minute flexures in the mechanical portions of the spectrometer are explained and plotted. A new idea for the very accurate measurement of the sines of Bragg angles by interferometry is discussed.

Improvements in the Precision of β-Ray Spectroscopy.
J.W.M. DuMond, Physics Today 5, 10-13 (December 1952)

The first successful tests of the new β-ray spectrometer are described. The results of these tests verified the correctness of many of the original calculations and laid the basis for further improvements.

(23) Low Angle X-Ray Diffraction with Long Wavelengths.
B. Henke and J.W.M. DuMond, Phys. Rev. 89, 1300 (1953)

A brief discussion is given of a new point focusing X-ray diffraction camera for very long wavelength x-rays. The results of one experiment on the determination of the size of Dow Latex spheres are given.

(24) Diffraction of Long Wavelength X-Rays.

Burton Henke. (Not published to date elsewhere. An article is in preparation.)

A comprehensive discussion (104 pages) of the theory, construction and application of the new long wavelength X-ray diffraction camera. Included is a rather complete analysis of long wave diffraction theory.

(25) Least-Squares Adjustment of the Atomic Constants - 1952.

J.W.M. DuMond, E.R. Cohen, Rev. Mod. Phys. 25, 691-708 (1953)

Recent precision experiments are discussed and are presented as input data for a least squares adjustment of the atomic constants. The methods used are explained. The revised values are completely tabulated. These data supersede all earlier values given by the authors and at the date of this final report are still our best recommendations.

(26) The Decay of $Ta^{183}$.

J.W.M. DuMond, H.C. Hoyt, P.E. Marmier and J.J. Murray Phys. Rev. 92, 202 (1953)

A brief report on investigations of the decay of $Ta^{183}$. The curved crystal spectrometer, a photographic spectrometer, and the $\beta$-ray spectrometer were used to locate and measure twenty-one $\gamma$-lines.

(27) A Precision Measurement at 24,500 Volts of the Conversion Constant $\lambda V$.

G.L. Felt, J.N. Harris, and J.W.M. DuMond, Phys. Rev. 92, 1160-1175 (1953)

A precision determination of the wavelength in x-units (Siegbahn scale) at the quantum limit of the continuous spectrum from a tungsten target sealed off

X-ray tube operating under an accurately stabilized and measured applied voltage, $V_H$ = 24,498.7 absolute volts (emu) is described. The aim was to obtain a precise determination of the conversion constant $V_A\lambda_s$ between X-ray wavelengths and quantum energy in electron volts. A comparison with other determinations of this type is given.

(28) The Spectroscopy of Nuclear Gamma-Rays by Direct Crystal Diffraction Methods.

J.W.M. DuMond. (To appear in Ergebnisse der Exakten Naturwissenshaften. A condensed version is also to appear as a chapter in K. Siegbahn's text on nuclear spectroscopy to be published by the North Holland Publishing Co.)

A comprehensive report (67 pages) covering the history of curved crystal spectroscopy from the early theory, through the construction and present applications of the 2-meter curved crystal spectrometer.

(29) The Variety of Our Sources of Information on Avogadro's Number and Other Constants.

J.W.M. DuMond and E.R. Cohen, Phys. Rev. 94, 1790 (1954)

This report explains in detail why the X-ray crystal density method is not the sole nor most significant determination of Avogadro's number. It cites thirteen ways of determining the value of this constant with comparable or better accuracy, but recommends only the least squares adjusted value since it is most compatible with the entirely of our existing information.

(30) Corrected Values of Tungsten K-Series X-Ray Wavelengths with the 2-Meter Curved Crystal Diffraction Spectrometer.

P. Snelgrove, Jassim El-Hussaini, and J.W.M. DuMond, Phys. Rev. 95, 1203 (1954)

This report tabulates the results of precision measurements of W-K$\alpha_1$, W-K$\alpha_2$, W-K$_{\beta_1}$, and W-K$\beta_3$ that were made to correct data published in 1949. The earlier experiment was performed before the calibration of the 2-meter spectrometer for mechanical flexure was completed.

(31) Gamma Transitions in $W^{182}$.

F. Boehm, P. Marmier and J.W.M. DuMond, Phys. Rev. 95, 864 (1954)

This reports briefly measurements of 27 $\gamma$-transitions in $W^{182}$ tabulating their quantum energies, relative intensities, conversion coefficients (obtained by comparison of the results of directly measured $\gamma$-rays with the crystal diffraction 2-meter instrument with the internally converted $\beta$-ray measurements made with the homogeneous field axial focusing magnetic spectrometer) and their inferred multipolarities. A complete level decay scheme with all spins and parities is given based upon the above data. A. Bohr has discussed these results in the light of the Bohr-Mottelson theory of collective motion and has been able to classify the level scheme into four distinct series of rotational spectra in good quantitative agreement with its predictions.

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